Mechanical Properties and Thermal Shock Resistance of Hot-pressed High-speed Steel

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A high-speed steel (HSS) powder with a chemical composition (mass%) of 81.91 Fe, 0.85 C, 4.03 Cr, 1.94 V, 4.88 Mo, and 6.01 W and with a median size 11.2 μm, was hot-pressed to a relative density higher than 99 % under a pressure of 39 MPa at 1323 K for 2 h in an Ar atmosphere. This dense HSS showed the following significantly high mechanical properties: tensile strength of 1360-1510 MPa with Weibull modulus 32.2, four-point flexural strength of 2280-3030 MPa with Weibull modulus 9.3. The hot-pressed HSS specimens were heated in air at 673-1273 K for 15 min and quenched into cold water at 273 K. The flexural strengths of quenched HSS specimens were divided into low and high strength groups. The strength of high strength group was close to that of as-hot-pressed HSS. The increase of quenching temperature difference decreased the strength of HSS in the low strength group. On the other hand, the HSS cooled slowly from 1273 K, showed a narrow strength distribution which was close to that of as-hot-pressed HSS. However, the slowly cooled HSS provided a low apparent Young's modulus and a significantly large deformation strain as compared with the mechanical properties of quenched HSS.
Key words: High-speed steel, Thermal shock resistance, Flexural strength, Tensile strength, Weibull modulus, Hardness

1. Introduction

The high-speed steel (HSS) consisting of Fe and several kinds of transition metal carbides has a high fracture toughness (25 ~ 28 MPa • $m^{1/2}$) and a high hardness (7.5 GPa in Vickers hardness) [1, 2]. This material is applied to cutting tool or wear–resistant materials. The use of HSS experiences a relatively high thermal shock because a coolant such as water or oil is flowed over the surface of heated HSS. To overcome the high thermal shock, a high strength is needed for HSS. The critical temperature difference (ΔT_c) to no crack formation for brittle materials is expressed by $\Delta T_c = \sigma(1-\nu)/\alpha E$, where σ is the tensile strength, ν the Poisson ratio, α the thermal expansion coefficient, and E the Young's modulus [3-5]. It is understood that the high σ, low α and low E are the effective factors to increase the thermal shock resistance [6, 7]. The substitution of the typical values for HSS, $\Delta T_c = 1000$ K, $\nu = 0.27$, $\alpha = 1.3 \times 10^{-5}$ K^{-1} and E = 240 GPa into the equation of critical temperature difference leads to $\sigma = 4274$ MPa [8]. To use HSS safely, a significantly high strength is required. This paper reports on the mechanical strength and the thermal shock resistance of HSS processed by hot-pressing at 1323 K. Usually, an HSS powder is heated above 1773 K to melt and solidified to a desirable shape during a cooling process. In this study, HSS was densified at a low temperature of 1323 K to suppress the grain growth of HSS, leading to the increased strength.

2. Experimental procedure
2.1 Materials

A high-speed steel powder (Mitsubishi Steel Mfg. Co., Ltd., Japan) has a cumulative particle size distribution of 4.4 μm / 10 %, 11.2 μm / 50 % and 24.9 μm / 90 % and a following chemical composition (mass%): 81.91 Fe, 0.85 C, 4.03 Cr, 1.94 V, 4.88 Mo, and 6.01 W. The true density of HSS powder measured by the pycnometer method using kerosene, was 7.931 g/cm^3. As-received HSS powder was formed in the sizes of 38 mm length, 25 mm width and 23 mm thickness, and heated to 1323 K at 10 K/min to sinter for 2 h in an Ar atmosphere under a pressure of 39 MPa with carbon die (FVH-5 type, Fuji Denpa Kogyo Co., Japan). The hot-pressed HSS was cooled to room temperature at 5 K/min. The density of hot-pressed HSS was measured in kerosine by the Archimedes method.

2.2 Strength measurement of hot-pressed HSS

The hot-pressed HSS was cut into test specimen shown in Fig. 1 to measure the tensile strength. The test specimen was polished with Nos. 600, 1200 and 2000 SiC papers. The tensile strength was measured at room temperature at a crosshead speed of 0.5 mm/min (AG-1 50 kN, Shimadzu Co., Japan). The fracture surface was observed by scanning electron microscope (SM-300, Topcon Co., Japan). As-hot-pressed HSS was also cut into test specimens 38 mm long, 4 mm wide and 3 mm thick and polished with Nos. 600, 1200 and 2000 SiC papers. Then, the flexural strength of polished specimen was measured at room temperature by the four-point flexural method, over spans of 30 mm (lower span) and 10 mm (upper span), at a crosshead speed of 0.5 mm/min (Model UTM-1-5000 BE, Toyo Baldwin Co., Japan). The measured strengths were analyzed by the Weibull distribution function (Eq. (1)),

$$F = 1 - \exp\left\{-\left(\frac{\sigma}{\sigma_0}\right)^m V\right\} \qquad (1)$$

where F is the fracture probability, σ the applied stress, σ_0 the scale parameter, m the Weibull modulus and V the effective volume of specimen. The accumulative fracture probability (F) of ith specimen was determined using the median rank method by Eq. (2),

$$F = \frac{i - 0.3}{n + 0.4} \qquad (2)$$

where n is the number of test specimens.

2.3 Thermal shock resistance

The rectangular HSS specimens were heated to 673, 1123 and 1273 K in air and kept for 15 min to ensure the thermal uniformity of specimens [9]. According to the phase diagram of the Fe-C system [10], α-Fe + Fe_3C and γ-Fe are formed at 673 and 1123 K, respectively, for the given chemical composition of HSS used. In the heating at 1273 K, γ-Fe is formed in the HSS. The HSS specimens were dropped into cold water at 273 K [11-13]. The flexural strength of quenched specimen was measured at room temperature by the four-point flexural method, over spans of 30 mm (lower span) and 10 mm (upper span). The surface of the quenched specimen was investigated by X-ray diffraction (CuKα, Model No.2013, Rigaku Co., Tokyo, Japan) and scanning electron microscope [14, 15].

3. Results and discussion

3.1 Tensile strength and flexural strength of hot-pressed HSS

The HSS powder was hot-pressed to a relative density higher than 99 %. Figure 2 shows a polished microstructure of as-hot-pressed specimen. The dispersed white grains of 0.32-1.58 μm size correspond to the transition metal carbides such as Fe_3C, VC, WC, Mo_2C and Cr_3C_2. The gray matrix is α-Fe. This microstructure represents the fine transition metal carbide particles-reinforced α-Fe matrix composite. Figure 3 shows the typical relationship between tensile or flexural stress and strain for the hot-pressed HSS. Both the

measurements provided the similar stress-strain curves. Both the testing methods showed a gradual decrease of Young's modulus with increasing strain, indicating the ductile properties. The fracture strength by flexural test was higher than that by tensile test.
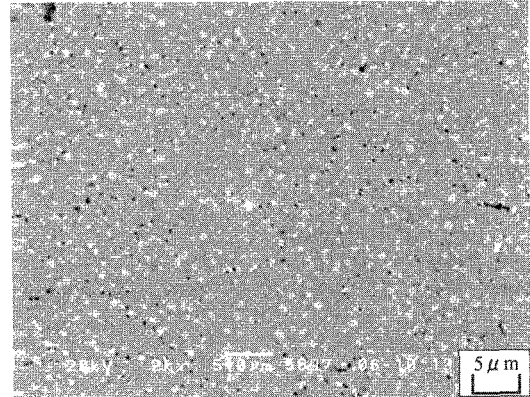

Fig. 2 A polished microstructure of as-hot-pressed HSS.
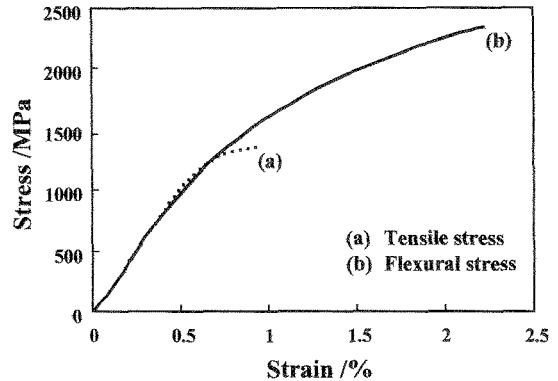

Fig. 3 Typical relationship between tensile or flexural stress and strain for the hot-pressed HSS.
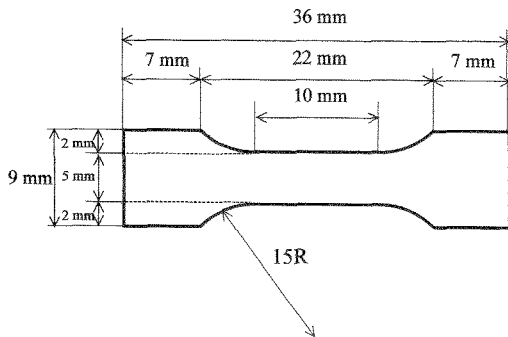

Fig. 1 Shape and size of as-hot-pressed HSS used in tensile strength measurement.
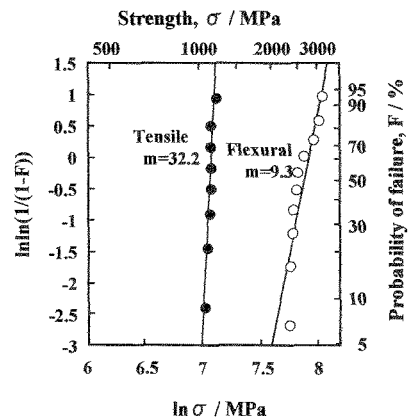

Fig. 4 Weibull plots of tensile and flexural strengths for as-hot-pressed HSS.

Figure 4 shows the Weibull plots of tensile and flexural strengths of hot-pressed HSS [16]. The tensile strength was in the range from 1360 to 1510 MPa. The mean tensile strength was 1430 MPa and the Weibull modulus was 32.2. Lee reported the tensile strength of 895-1034 MPa for the HSS with a chemical composition (mass%) of 72.7-80.3 Fe, 0.99-1.13 C, 0.65-1.10 Si, 0.35-0.52 Mn, 0.025 P, 0.002-0.045 S, 1.68-1.71 Cr, 5.46-6.00 Mo, 1.66-2.30 W, 1.05-1.47 V and 7.80-13.00 Co, which was prepared by the melting forging method [17]. Fujita et. al measured the tensile strength of 1800 MPa of HSS (> 99 % theoretical density) with a chemical composition (mass%) of 63.67 Fe, 2.35 C, 0.40 Si, 0.15 Mn, 4.35 Cr, 7.05 Mo, 5.78 W, 5.95 V and 10.30 Co, which was prepared by hot isostatic pressing at 1473 K for 4 h [18]. The measured strength of HSS hot-pressed in this experiment was close to the value of HSS by hot isostatic pressing.

Figure 4 shows the flexural strength distribution of hot-pressed HSS. The flexural strength was in the range from 2280 to 3030 MPa. The mean strength and the Weibull modulus were 2550 MPa and 9.3, respectively. As seen in Fig. 4, the flexural strength was two times as high as the tensile strength. This difference of strength is explained by the effective volume in the each testing method. Equation (3) expresses the relationship between mean strength (σ) and effective volume (V) for tensile (T) and flexural (F) strength measurement,

$$\frac{\sigma_T}{\sigma_F} = \left(\frac{V_F}{V_T}\right)^{1/m} = \left(\frac{V_F'}{V_T}\frac{m+2}{4(m+1)^2}\right)^{1/m} \quad (3)$$

where m is the Weibull modulus of flexural strength and V_F' is the volume between lower span for the flexural testing specimen [19, 20]. Equation (3) predicts the σ_T/σ_F ratio to be 0.80 for m = 9.3 and explains the lower value for the tensile strength than for the flexural strength. The

measured σ_T/σ_F ratio was 0.56 and lower than the calculated ratio.

3.2 Thermal shock resistance of HSS

In the as-hot-pressed HSS and quenched HSS, α-Fe and Fe_3C were identified, indicating the phase transition from γ-Fe to α-Fe during the cooling process. However, the surface of HSS cooled slowly from 1173 K in air was oxidized to Fe_2O_3. In addition, it was found by the observation of cross section of the quenched HSS with scanning electron microscope that the surface of quenched HSS was also oxidized to Fe_2O_3. The thickness of the surface Fe_2O_3 layer was 50 ± 5 μm at 673 K, 100 ± 10 μm at 1123 K, 200 ± 20 μm at 1273 K of heating temperature, and 220 ± 20 μm after the slow cooling from 1273 K, respectively. Since the oxide layer was porous and weak, the oxide-free sizes was used for the strength calculation of quenched or slowly cooled HSS.

Figure 5 shows the flexural stress-strain relationships for the quenched HSS and slowly cooled HSS. No significant difference in the stress-strain curves was seen between the highest strength and lowest strength specimens at each quenching temperature difference. Their stress-strain curves, except for the specimen with
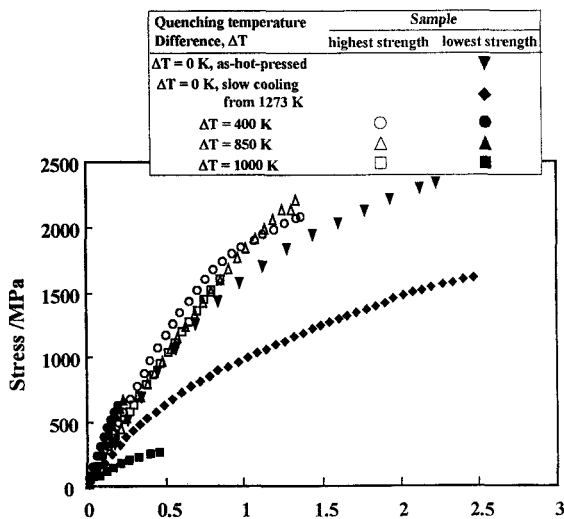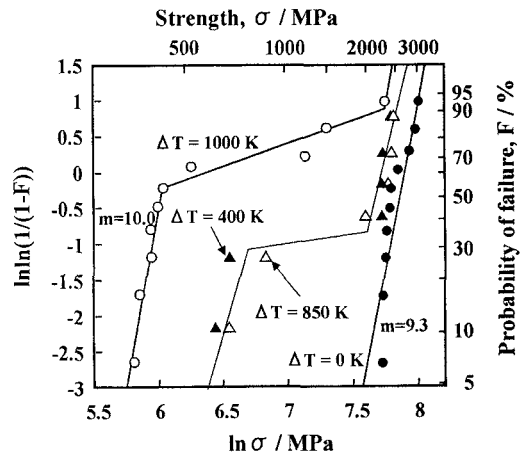
Fig. 6   Weibull plots of flexural strength of quenched HSS.

Fig. 5   Flexural stress-strain relationships for the quenched HSS and slowly cooled HSS with the lowest and highest strengths.
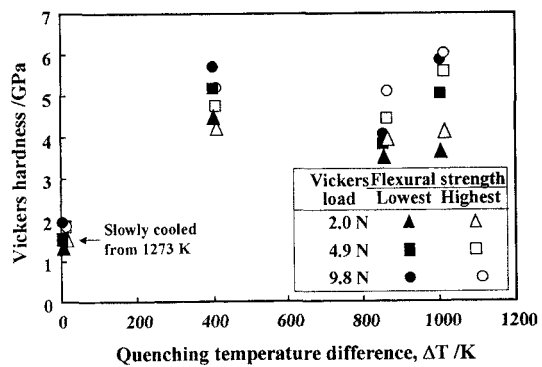
Fig. 7   Relationship between Vickers hardness of HSS and quenching temperature difference.

the lowest strength at quenching temperature difference of 1000 K, were very close to the deformation behavior of as-hot-pressed HSS. That is, the fracture strength was dependent on the allowed strain. On the other hand, the slowly cooled HSS showed a low apparent Young's modulus and a significantly large deformation strain. Therefore, the slow cooling of hot-pressed HSS enhanced the ductility in the deformation behavior.

Figure 6 shows the Weibull plots of flexural strength of the quenched HSS. The thermal shock of $\Delta T = 400$ and 850 K reduced the strength of HSS to 630-2210 MPa and 700-2440 MPa, respectively. The larger thermal shock of $\Delta T = 1000$ K provided a wide strength distribution of 340-2320 MPa. On the other hand, the HSS cooled slowly from 1273 K, showed a narrow strength distribution of 1640-2460 MPa. The data for quenched HSS were possible to divide into low and high strength groups. The Weibull modulus of low strength group (m = 10.0) for HSS quenched with $\Delta T = 1000$ K was close to that of strength for as-hot-pressed HSS ($\Delta T = 0$ K). As seen in Fig. 6, the larger ΔT increases the fraction of HSS specimens in the low strength group and shifted the strength of the low strength group to lower values. On the other hand, the high strength group was not influenced by the magnitude of ΔT.

Figure 7 shows the relationship between Vickers hardness of HSS and quenching temperature difference for two samples with the lowest and highest strengths at each quenching test. The hardness was measured on the oxide layer-free surface at 2.0-9.8 N of load. The HSS cooled slowly from 1273 K was significantly soft and the quenched HSS showed a higher hardness than the slowly cooled sample. The hardness of quenched HSS was almost independent of the flexural strength.

4. Conclusions

(1) As-hot-pressed HSS showed the significantly high flexural strength of 2280-3030 MPa with a Weibull modulus of 9.3. The tensile strength was in the range from 1360 to 1510 MPa, giving a high Weibull modulus of 32.2. The difference of strength for both the testing methods was explained by the effective volume of HSS and Weibull modulus.

(2) The flexural strength of HSS quenched from 673-1273 K was divided into low and high strength groups. The larger quenching temperature difference (ΔT) increased the fraction of HSS specimens in the low strength group and shifted the strength of the low strength group to lower values. The strength of high strength group was not influenced by the magunitude of ΔT and close to the strength of as-hot-pressed HSS.

(3) The slow cooling of HSS from 1273 K in air gave small influence on the flexural strength. However, the slowly cooled HSS gave a lower apparent Young's modulus and a lower hardness as compared with the mechanical properties of as-hot-pressed HSS. The Vickers hardness of quenched HSS was independent of the flexural strength and higher than that of slowly cooled specimen.

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